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Risk analysis of roof fall and prediction of damaged regions at retreat longwall coal mining face

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Sajjad Aghababaei[1]; Gholamreza Saeedi[2]; Hossein Jalalifar[3]

[1] Shahid Bahonar University of Kerman, Department of Mining Engineering, Kerman, Iran, https://orcid.org/0000-0002-2981-8987
[2] Shahid Bahonar University of Kerman, Department of Mining Engineering, Kerman, Iran, https://orcid.org/0000-0003-3161-3603
[3] Shahid Bahonar University of Kerman, Mining and Petroleum Engineering Department, Kerman, Iran, https://orcid.org/0000-0003-4610-5169

Abstract

This study presents a model based on rock engineering systems (RES) to evaluate the risk of roof falls and determine damaged regions, using recorded roof falls, prior to mining with a retreat from a longwall face. In this regard, a case study was considered to examine the model. The results showed that the level of determined risk has an acceptable correlation with the special roof fall (SRF), with R-squared value (R^2) equal to 0.792 for all estimated vulnerability indexes (VIs) in considered longwall panels. By investigating and comparing the evaluated values of VI in considered panels and their corresponding recorded roof falls, damaged regions were distinguished from undamaged regions. Based on these investigations, four classes including safe, moderate, danger, and critical regions were determined to identify the safe and damaged regions prior to the mining operation. The results of the research showed that the identification of damaged regions is feasible to provide a detailed operation plan to control roof falls in longwall mining faces through the developed approach. The RES-based model could be used for the same conditions and the presented methodology could be applied to other parts in underground coal mines.

Keywords:
Roof fall; Rock engineering systems; Damaged regions; Longwall method; Coal mining

1. Introduction

Coal mining by the underground method has been always one of the most dangerous mining methods, with the highest rate of injuries, fatalities, and damages. Working faces in underground coal mines, especially longwall faces, requires continuous advancing and the avoidance of stoppages since interruptions in progress could cause roof falls. Roof falls are the most critical cause of damages in underground coal mines. So, presentation and development of a method to identify and control roof falls is always a priority. A roof fall at a longwall face is defined in three dimensions as shown in Figure 1. The third dimension is the length of a fall that is specified along the face line.

Recently, extensive studies have been carried out to assess risks and control the roof falls in underground coal mines. In this paper, some of these studies are mentioned. **Molinda et al. (2000)** stated that the coal mine roof rating (CMRR) is the foremost indicator to predict the roof fall rate. They divided the areas into the ranges of safe to dangerous by evaluating the relationship between the recorded falls and CMRR. **Deb (2003)** applied an approach to analyse the roof fall rate using fuzzy reasoning techniques in coal mines. The presented outline involved three variables consisting of the intersection diagonal span (IDS), the primary roof support (PRSUP), and CMRR. **Duzgun and Einstein (2004)** presented a risk and decision analysis methodology to assess and manage the risk of roof falls. In this study, the time intervals between the roof fall accidents and the number of roof falls each year were considered for the probability assessments (objective method). Decision analysis has involved two actions, consisting of "do nothing" and "support improvement". **Maiti and Khanzode (2009)** developed a relative risk model for roof and side fall fatalities by three safety performance indicators including potential fatalities, relative risk of fatalities and safety measure effectiveness. **Palei and Das (2009)** conducted a logistic regression model to predict the roof fall risks in board and pillar workings in coal mines and also investigated the relationship between the major contributing parameters and accidents. They considered seven variables consisting of geological, design and operational factors for their model. **Ghasemi et al. (2012)** provided a method for the evaluation of roof fall risk using semi-quantity techniques. In this regard, they identified the effective parameters and then explained the role of each parameter on roof falls. In this research, eighteen

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Corresponding author: Gholamreza Saeedi
gsaeedi@uk.ac.ir

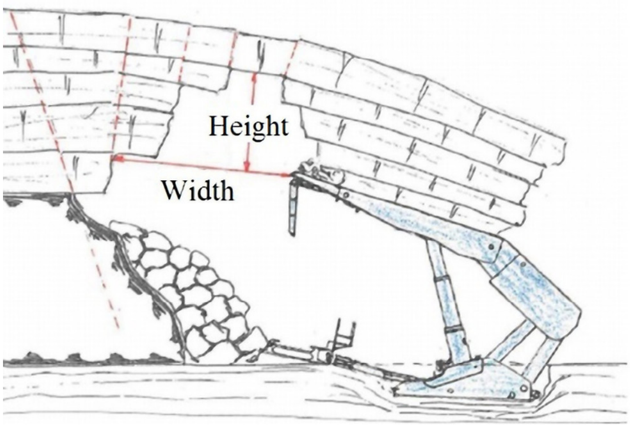

Figure 1: A roof fall at a longwall face, after (**Prusek et al., 2017**)

geological, design and operational parameters were considered for the presented model. **Razania et al. (2013)** used a fuzzy inference system to predict the rate of roof falls. CMRR, depth of cover, mining height, intersection diagonals and PRSUP were considered as effective parameters. They investigated the performance of the presented approach by comparison of actual and predicted roof fall rates. **Prusek et al. (2017)** determined the major factors influencing the stability of a roof in retreat from a longwall panel and then provided a practical method for assessing the risk of roof fall based on these factors. In this study, an investigator used to determine the probability and potential consequences of roof falls. **Canbulat et al. (2017)** assessed risks of sinkhole occurrences associated with shallow board and pillar mining. **Zhang et al. (2018)** conducted a numerical modelling study to investigate the effect of the longwall retreat direction on stress concentrations in the headgate and then discussed the causes and risks of roof falls in the longwall belt entry, and mitigation measures for roof-fall risks. **Luo et al. (2019)** presented a model to evaluate the risk of ground control collapse in goaf based on unascertained measures. **Yong et al. (2019)** proposed an object-oriented model base framework that realizes model management and a model reused to evaluate the geological hazards in mines effectively and systematically. **Zilong et al. (2019)** presented a new risk assessment model incorporating the stability of individual pillars and the load transfer between pillars was proposed to investigate the cascading failure of pillar sections.

RES have been widely applied in the field of mining and civil engineering. In the field of underground mining, these studies are listed including the assessment of rock mass cavability in block caving mines **(Rafiee et al. 2015)**, development of a destressability index methodology for the assessment of the likelihood of success of a large-scale confined destress blast in an underground mine pillar **(Andrieux and Hadjigeorgiou 2008)**, evaluation and classification of coal spontaneous combustion potential in coal mines **(Saffari et al. 2013)**, predicting the level of risk due to out-of-seam dilution (OSD) in longwall faces **(Bahri et al. 2014)**, analysing and predicting the floor failure mechanisms at longwall face **(Aghababaei et al. 2015)**, quantifying rock mass behavior underground **(Adoko et al. 2016)**, geohazard risk assessment in coal mines **(Vaziri et al. 2017)**, evaluating the comprehensive outburst index in coal mines **(Zhou et al. 2017)**, determination and assessment of coal bed methane potential in coal mines **(Ghanbari et al. 2018)**, the application of a system of thinking-based techniques for the assessment of rock mass cavability in block caving mines **(Rafiee et al. 2018)**, predicting the face advance rate and determining the operation efficiency in retreat longwall mining **(Aghababaei et al. 2019)**, introducing a coal seam methane drainageability index (CMDI) for predrainage techniques in a working mine **(Najafi and Rafiee 2019)**, and presenting an index entitled rock burst damage scale (RDSI) to predict the scale of damage due to rock burst hazards **(Ning et al 2019)**.

This research provides an approach to identify the damaged regions, refers to regions where the roof falls happen, in retreat from longwall mining panels with the aim of planning crisis management prior to mining. For this purpose, a model based on RES is proposed to evaluate the risk of roof falls and identifying the damaged regions, using recorded roof falls. Performance evaluation of the model requires a suitable case study. So, a case study is considered and the presented model is examined.

2. Case Study

The case study consists of six longwall panels including E_0, E_2, E_3, W_0, W_1 and W_2 in Parvadeh-I coal mine (see **Figure 2**). The E_1 panel is not included due to lack of data. Roof falls at the Parvadeh-I coal mine cause a lot of damages. Some of these falls were so large that they caused a reduction of the face advance rate to 0.1 m/day several times and a lot of damages to the extraction equipment. In this mine, floor failure is other instability in the longwall face which is in close interaction with roof fall.

Parvadeh-I is in the south-east of Tabas, Iran. In this mine (IRASCO et al., 2005a; IRASCO et al., 2005b), the extracting coal seam is inclined 22 degrees with a thickness of 2 m and the main surrounding geological units are mudstone, siltstone and sandstone. The direction of larger horizontal stress is from north east to south west. Also, Table 1 provides a summary of information about the considered panels. The powered supports are controlled by a manual control system in Parvadeh-I.

3. Method

3.1. A brief summary of rock engineering systems

Hudson (1992) presented an approach named rock engineering system (RES) to analyse the interaction between the effective parameters and components involved in rock mass for evaluating and answering complex en-

Figure 2: Considered longwall panels in Parvadeh-I

Table 1: A brief information of considered longwall panels

Panel code	Depth (m)	Panel width (m)	Average dip of coal seam (degree)	Description
W_0	180	207	<15	Extracted, Roof falls with height 0.3 to 0.9 m are not recorded
W_1	260	190.5	15.7	Extracted, Roof falls with height 0.3 to 0.9 m are not recorded
W_2	365	205.5	12.8	Extracted, Roof falls with height 0.3 to 0.9 m are not recorded
E_0	95	198	12.4	Extracted, Roof falls with height 0.3 to 0.9 m are not recorded
E_2	250	213	24.9	Extracted
E_3	368	207	19	Is extracting in Sep. 2018, Roof falls with height 0.3 to 0.9 m are not recorded

gineering issues. The RES determines and quantifies the interaction between parameters involved in a system. This process can be done by an interaction matrix as the key element of RES (see **Figure 3**). An n*n interaction matrix created by n parameters affecting the system. The off-diagonal positions in the matrix are filled by values describing the degree of interaction between the parameters. This research has adopted the "expert semi-quantitative" (ESQ) method **(Hudson, 1992)** for numerically coding the interaction matrix, in such a way that 0 is assigned for no interaction, 1 for weak, 2 for medium, 3 for strong, and 4 for critical interaction respectively. According to **Figure 3**, each particular parameter is denoted as coordinates (C, E), C and E are cause and effect. The interaction matrix helps in determining the weighting of each effective parameter within the system by **Equation 1**, where C_i and E_i are the cause and effect of the ith parameter, respectively.

$$a_i = \frac{(C_i + E_i)}{(\sum_{i=1}^{n} C + \sum_{i=1}^{n} E)} \tag{1}$$

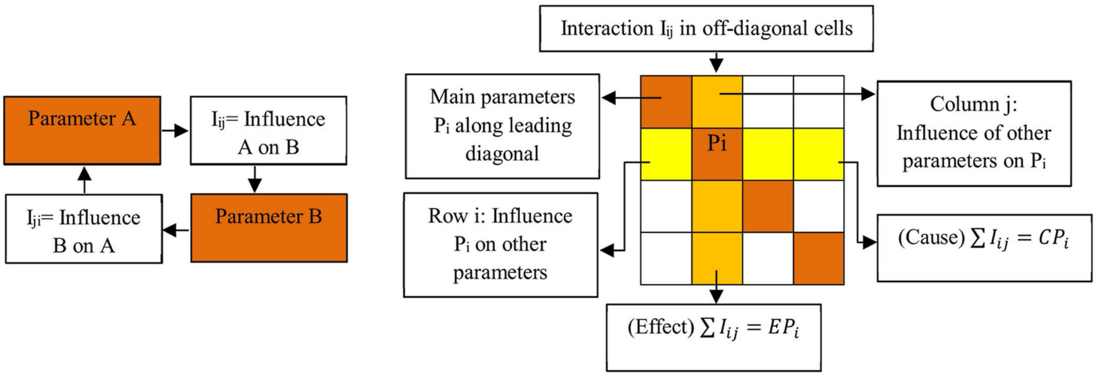

Figure 3: A general view of interaction matrix including principle of interaction between two parameters and matrix coding (taken after **(Hudson, 1992)**)

3.2. Applied approach for the research

The approach is based on estimating the risk of roof fall in each panel and comparing it with the corresponding roof fall which occurred previously to identify the damaged regions in the extracted panels and use the obtained results to predict the damaging regions in the next longwall panels. Here, **Equation 2** presented by **Benardos and Kaliampakos (2004)** is used to determine the risk of roof falls. Evaluating the capability of the provided RES-based model is carried out by investigating the relationship between the average of estimated roof fall risks and special roof fall (SRF) for the considered panels. A special roof fall in a panel is determined by **Equation 3**. In **Equations 2** and **3**, VI is the vulnerability index referring risk of a roof fall, a_i is the weighting of the ith parameter (evaluate by RES), Q_i is the value (rating) of the ith parameter, Q_{max} is the maximum value assigned for the ith parameter (normalization factor), TVRF is the total volume of roof falls in the panel (m^3) and EAP is the extracted area of the panel (m^2). VIs of 0 and 100 show the lowest and highest risk level, respectively.

$$VI = 100 - \sum_{i=1} a_i \frac{Q_i}{Q_{\max}} \tag{2}$$

$$SRF = \frac{TVRF}{EAP} \tag{3}$$

Accurate calculation of VI in each panel requires the organization of a database along each panel gate. Therefore, for the considered case study, the length of each gate was divided into intervals with equal distance and required data by all of the recorded and surveyed geological and geomechanical information determined for them. Then, VI for each interval is determined and the results are used to determine the corresponding VI of each recorded roof fall. In the present study, 486 datasets were collected along all the considered panel gates to evaluate the risk of roof falls. In the following analysis, information regarding 321 recorded roof falls (for each roof fall, two corresponding VIs is assigned, one in tailgate and another in maingate of each panel, so total number of corresponding VIs for roof falls are 642) was collected and processed.

3.3. Presenting the RES-based model

To generate the reaction matrix, nine main effective parameters on roof falls in a longwall mining face are considered in the RES-based model including CMRR (P_1), Coal- roof interface strength (P_2), safety factor of face (P_3), the ratio of joint spacing to cutting depth at face (P_4), longitudinal inclination of face (P_5), panel width (P_6), rock mass rating (RMR) of floor (P_7), type of control system of Powered supports (P_8) and Distance of roof layers overhanging (cantilever) from roof line at face (P_9). The safety factor of face (SF) be estimated by **Equation 4 (Aghababaei et al., 2015)**, where f is the correction factor of joint orientation at a coal seam. The correction factor f is equal to (1-B) where B is the orientation factor for a critical joint set, $\sigma_{c.w}$ is the strength of first 0.75 m of the coal face in depth and σ_{yy} is the vertical induced stress on the 0.75 m distance of the coal face.

$$SF = \frac{\dfrac{\sigma_{c.w}}{\sigma_{yy}}}{f} \tag{4}$$

The interaction matrix was created based on the nine effective parameters and its results are shown in **Table 2**. The coding of a matrix was carried out based on experiences and views of experts in the field of longwall mining. Also, **Figure 4** indicates the a_i values determined by **Equation 1** for each parameter. According to these results, P_6, P_1, P_3 and P_8 appeared to have more interaction in the system.

Table 2: Generation of interaction matrix

P_1	2	1	0	0	3	0	2	0
1	P_2	1	0	0	0	0	0	0
0	1	P_3	0	0	1	0	1	0
2	0	1	P_4	0	2	1	1	0
0	0	1	0	P_5	1	0	1	0
0	0	1	0	0	P_6	0	1	0
0	0	1	0	1	3	P_7	1	0
0	0	0	0	1	2	0	P_8	0
3	0	2	1	1	1	0	1	P_9

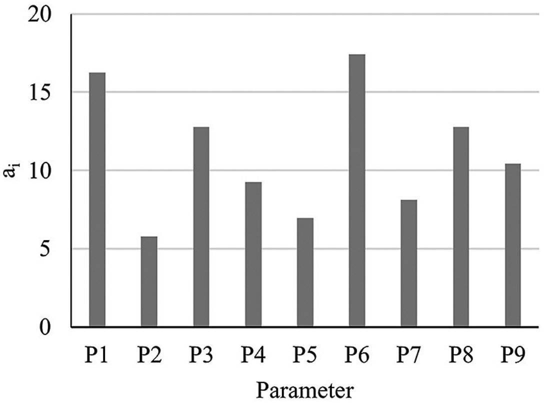

Figure 4: Determined a_i values of the parameters

Rating of the parameters is essential to calculate the Q_i/Q_{max} in **Equation 2**. So, the rating was carried out based on their influence on the roof falls (see **Table 3**). In this rating, 0 indicates the worst condition (maximum probability of the occurrence of a roof fall) and a higher number, for example 4 in the rating of P_1, the best condi-

Table 3: Rating of the parameters

Code of parameter	Value/description and rating						
P1	Value	<21	21-40	41-60	61-80	81-100	
	Rating	0	1	2	3	4	
P_2	Value	Week	Moderate	Strong			
	Rating	0	1	2			
P_3	Value	<0.75	0.75-1	1-1.25	1.25<		
	Rating	0	1	2	3		
P_4	Value	<0.25	0.25-0.5	0.5-0.75	0.75-1	1-1.25	1.25<
	Rating	0	1	2	3	4	5
$_{P}5$	Value	<15	15-30	30-45	45<		
	Rating	3	2	1	0		
P_6	Value	<100	100-150	150-200	200-300	300<	
	Rating	3	4	2	1	0	
P_7	Value	<21	21-40	41-60	61-80	81-100	
	Rating	0	1	2	3	4	
P_8	Value	Manual Control	Automatic Control	Electrohydraulic Control			
	Rating	2	4	5			
P_9	Value	No Present	$h_{im.max}>$	$h_{im.max}\leq$ & $\leq$20 m	20 m<		
	Rating	1	0	4	3		

tion (minimum probability of the occurrence of a roof fall). For P_9, $h_{im.max}$ is the maximum caving height of immediate roof which can be determined by **Equation 5 (Peng, 2006)**. In **Equation 5**, H_f is the mining height at the longwall face and K is the volumetric expansion coefficient of caved rock.

$$h_{im.max} = \frac{H_f}{K-1} \tag{5}$$

Determining the intervals for rating P_1 and P_7 were carried out based on five classes of rock mass quality including "very poor rock", "poor rock", "fair rock", "good rock" and "very good rock". According to the lack of quantitative data, a qualitative rating was considered for P_2 and Q_i was determined based on the lithology of strata. P_3 was rated in four classes based of the safety factor of the face. Bound of last class was determined based on the minimum recommended SF for design in rock. A rating of P_4 was considered in six classes based on the number of joints into the exposed span created by a cutting machine and the best condition is when two joints are not simultaneously located in the exposed span at the front of the roof. A rating for P_5 was carried out in four classes. Faces with an inclination of less than 15 degrees and more than 45 degrees have the best and worst operation conditions, respectively. Increasing the inclination increases the required support load, decreases the face advance rate and creates other problems in longwall panels. Coal seams with an inclination of more than 45 degrees can rarely be mechanized due to the worst operation conditions. A rating of P_6 was considered based on **Aghababaei et al. (2015)**. A qualitative rating was adopted for P_8. Using the automatic control

Table 4: Categorizing roof falls at the longwall face based on the required support operation and their hazards at the Parvadeh-I coal mine

Type of roof fall	**Height of roof fall (H)**	**Description**
Local	H<0.3	The roof support operation is not required for this type of roof fall. Dilution is the most important hazards of this type.
Small	0.3≤H≤1.5	For this type of roof fall, a support operation rarely causes delay in face advancing. Roof support by forepoling and crib are usual for this roof fall type at Parvadeh-I coal mine.
Moderate	1.5<H≤5	Roof support by forepoling and crib, and in a few cases, using the four-ply and filling by chaff or geofoam are applied for this roof fall at the Parvadeh-I coal mine.
High	H>5	This type with any length may cause the serious problems. Roof support by four-ply and filling by chaff or geofoam are applied for this roof fall type at the Parvadeh-I coal mine.

Table 5: Statistics of recorded roof falls in the considered panels

Type of roof fall	Recorded Number	Mean of length (m)	Range of length	Mean of height (m)	Range of height	Mean of width (m)	Range of width
Small	172	15	1.5-183	0.7	0.3-1.5	0.7	0.5-3
Moderate	135	10.9	1.5-43.5	3	1.6-5	1.5	0.5-5.7
High	14	9	3-19.5	8.7	6-20	2	0.5-4

system improves the operation significantly compared to the manual control which is not the same case with a change from an automatic control to an electrohydraulic system. The division for P_8 was based on this point that locating a strong cantilever layer into $h_{im.max}$ creates the highest pressure on powered supports.

4. Definition of damaged regions and categorizing the types of roof fall

Damaged regions are parts of the panels with a high probability of roof falls. In these regions, the size of a roof fall is considerable and needs to be supported. If the size of a roof fall is very high, it can cause very serious problems. Height is the most important dimension of a roof fall. The severity of instability and the degree of the required support operation is a function of the falling height. Therefore, a categorization was presented based on the height of a recorded roof fall in the Parvadeh-I coal mine (see **Table 4**). Due to the low importance and the lack of the need to support the local roof falls, no fall with a height of less than 0.3 m was recorded in the longwall faces of this mine. A statistical description of the data regarding recorded roof falls is shown in **Table 5**.

5. Results and discussion

The presented model was examined on the considered case study and its results are discussed in this section. A description of the determined VIs on the case study is outlined in **Table 6**. The R-squared value (R^2) between the SRF and estimated average of VIs is presented in **Figure 5** for all estimated VIs. To determine the influence of unrecorded small roof falls with a height of 0.3 to 0.9 m in E_0, E_3, W_0, W_1 and W_2, an equivalent volume of small roof falls (with a height of 0.3 to 0.9 m) was calculated for these panels and added to the recorded volume of roof falls of each panel and then a new SRF was determined. The new results are presented in **Figure 6**. This calculation was carried out by an average of height, length and width of small recorded roof falls in the height range of 0.3 to 0.9 m in the E_2 panel, and also the ratio of small roof fall number to sum number of the moderate and high roof falls in the considered panel.

Table 6: Statistical description of determined VIs (omit outlier data from E_3)

Code of panel	Ave. *VI*	Min *VI*	Max *VI*	St. Dev. of *VIs*	Outlier data (based on ±2SD) %
E_0	46.3	44.1	55.8	3.3	3.8
E_2	71.1	61.7	83.5	6.2	0
E_3	61.4	56.3	66.6	2.2	0
W_0	53.6	50.0	63.4	4.9	0
W_1	49.4	44.9	62.7	5.0	6.25
W_2	52.4	52.2	54.6	0.6	6.0

In this research, the relationships of the panel width, face inclination, ratio of joint spacing to cutting depth, safety factor of face, CMRR and floor RMR (quantitative parameters) with the SRF were investigated and results are presented in **Figure 7**, respectively. A statistical analysis of the average amounts of parameters for the considered case study is illustrated in **Table 7**. In this regard, a sensitivity analysis was applied to determine the effect of each of these parameters on SRF (see **Table 8**).

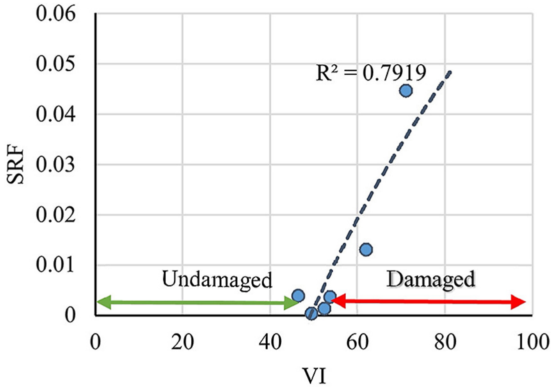

Figure 5: Correlation between VIs and SRF, a logarithmic regression analysis

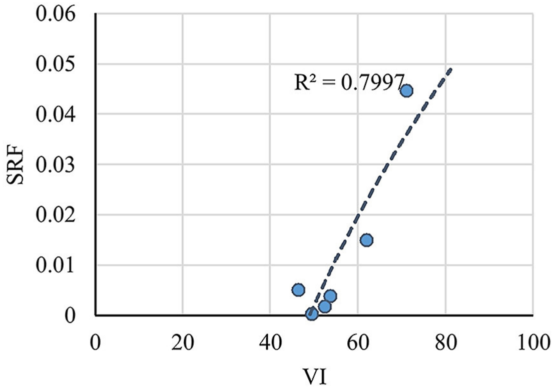

Figure 6: Correlation between VIs and SRF, add equivalent not recorded small roof fall, a logarithmic regression analysis

Table 7: Statistical description of parameters for considered case study (omit outlier data from detail data of P_4)

Parameter	**Mean**	**Min**	**Max**	**St. Dev.**	**Outlier data (based on ±2SD) %**
Panel width (m)	203.5	190.5	213	7.97	0
CMRR	43.2	33.07	50.38	7.55	0
Ratio of Joint spacing to cutting depth	1.22	0.38	1.88	0.489	0
Safety factor of face	1.42	0.74	3.08	0.89	0
Face inclination (degree)	16.3	12.4	24.9	4.9	0
Floor RMR	36.2	31.2	42	3.9	0

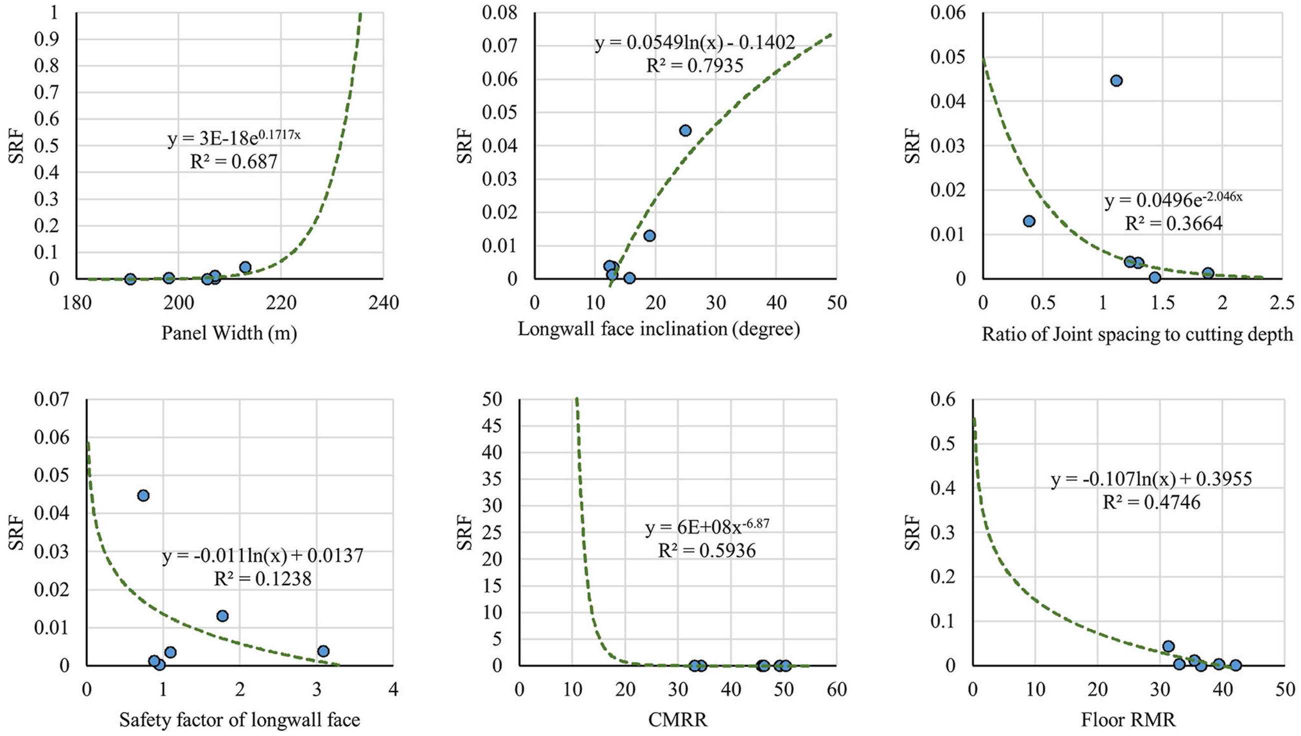

Figure 7: Correlation between parameters P_6, P_5, P_4, P_3, P_1 and P_7 with SRF (an exponential, logarithmic, regression, exponential, logarithmic, power and logarithmic analyses, respectively)

Table 8: Variations percentage of SRF with increase of each parameter, variation percentage investigated in the direction of increase the SRF

Parameter	***SRF* variation percentage with 10% variation**	***SRF* variation percentage with 20% variation**	***SRF* variation percentage with 30% variation**	***SRF* variation percentage with 50% variation**	***SRF* variation percentage with 70% variation**	***SRF* variation percentage with 90% variation**
Panel Width	2,511	68,071	1.77×10^6	1.21×10^9	8.27×10^{11}	5.63×10^{14}
CMRR	106	363	1,059	11,597	390,900	7.41×10^8
Floor RMR	1,427	3,023	4,832	9,389	16,309	31,191
Ratio of Joint spacing to cutting depth	85	241	531	2,052	7,245	24,969
Safety factor of face	72	152	243	472	820	1,568
Face inclination	22	41	59	92	120	145

To analyse the recorded roof falls and perform an accurate determination of the boundary between the undamaged and damaged regions, statistical analysis was performed. Frequency distribution of the recorded roof falls based on corresponding calculated VIs are shown in **Figure 8** for small and moderate falls, high falls and all of the corresponding roof falls. To construe the relationship between the recorded roof falls and the calcu-

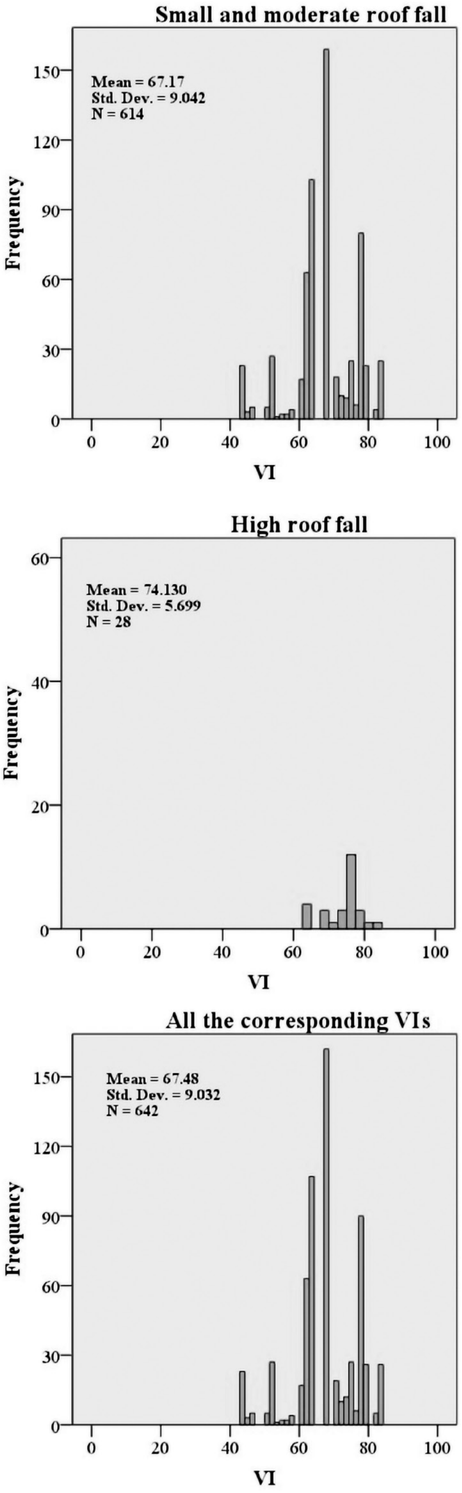

Figure 8: VI-Frequency distribution graph about recorded roof falls

lated VIs, statistical results are illustrated in **Table 9**. According to the results (see **Figure 8** and **Table 9**), classification of the damaged and undamaged regions was performed (see **Table 10**). In the following image, the regions were mapped in the considered panels based on the presented classification and results of the model (see **Figure 9**).

The boundary between the undamaged and damaged regions is shown in **Figure 5** where the regression line intersects with the horizontal axis. VI at this boundary is equal to 49 where the SRF is equal to 0. The accurate value of VI at boundary of undamaged-damaged regions was determined to be equal to 46 according to the obtained results from the statistical investigation of recorded roof falls (see **Table 9**).

In usual conditions, the intensity and volume of roof falls increases under the worst geotechnical conditions; which is noticeably demonstrated according to the results. The extension of continuous very high risk values in a large critical region may cause limiting of the panel in this region before mining or stopping the operation and relocation of the longwall face during mining.

Accurate determination of effective parameters on the system/hazard has a very important role in achieving the actual results. Comparing the parameter value with values of relevant hazards or options can be one of the criteria to perform this judgement so that the obtained results indicate there is a relationship for the proposed model.

The results demonstrated that one of the best ways to identify the damaged and undamaged regions is through the determination of the values of relevant hazards (roof falls) in the regions and investigating their relationship with the corresponding risks (VIs). This process could result in the determination of the boundary between the undamaged and damaged regions. However, accuracy of the results depends on the model validation. So, valuation of the model is very determinant.

There are criteria that could be considered to validate the model. One of the most important criteria is investigating the relationship outputs of the model and the values of relevant hazards. Studying the relationship between the values of selected effective parameters and the values of relevant hazards could be another auxiliary criterion for this purpose. It could be called the verification of selected parameters. The results proved that the presented model is at an acceptable level.

Table 9: Statistical results on type of roof fall

Type of roof fall	**Min. *VI***	**Max. *VI***	***VI* at 5% cumulative percent**	***VI* at 10% cumulative percent**	**Skewness**
Small and Moderate	44	84	46	52	-0.55
High	63	84	63	63	-0.71
Whole of roof falls	44	84	50	54	-0.58

Table 10: Categorizing the damaged and undamaged regions on a roof fall at longwall panels

Region code	**Range of *VI***	**Description**
Safe	0 to 46	In these regions no significant roof fall has occurred. The majority of roof falls are in local and rarely small scales.
Moderate	46 to 52	The majority of roof falls are in small and rarely moderate scales. Negligence in these regions can provide a worse condition.
Danger	52 to 63	In these regions, the size of falls is considerable. Roof falls increase operation costs and decrease productivity. Timely support operation decreases the volume of fallings. Negligence in these regions can lead to a critical condition.
Critical	63 to 100	Large dimension of a roof fall that may cause very serious problems.

6. Conclusion

The obtained results from testing the RES-based model on the considered case study showed that there is an acceptable correlation between the value of the determined risk and special roof fall (SRF). These results indicated that the presented RES-based model could be used to identify the damaged regions and predict the damaging regions prior to the mining operation.

Statistical investigations of recorded roof falls showed that along with an increase in the estimated VIs, the number and volume of the roof falls increased, which is quite consistent with reality. By investigating and comparing the evaluated values of VI in the considered panels and their corresponding recorded roof falls, the damaged regions are distinguished from the undamaged regions. Based on these investigations, four classes including safe, moderate, danger and critical regions were used to classify and identify the safe and damaged regions prior to mining operations. An accurate value of

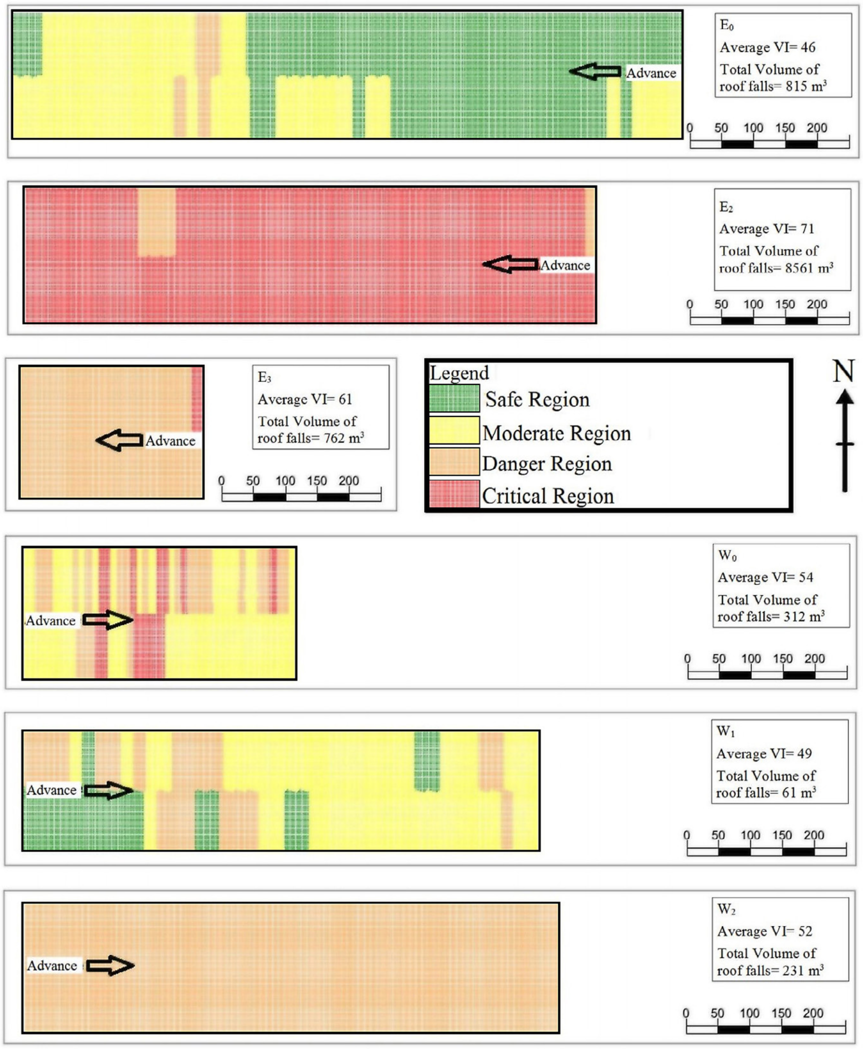

Figure 9: Identifying the undamaged and damaged regions by the RES-based model and the recorded roof falls

VI at the boundary of undamaged-damaged regions was determined to be equal to 46.

The presented methodology provides a reliable tool to determine the damaged regions before operations that could be used for all parts of underground coal mines. This methodology could provide a fantastic tool to avoid the application of special arrangements and additional costs in unnecessary regions and reduce the damage and injury rate due to the failure to consider special measures in critical regions.

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SAŽETAK

Analiza rizika od pada krovine i predviđanje oštećenja područja pri rudarenju ugljena povlačenjem širokoga čela

U ovome radu prikazan je model utemeljen na sustavima inženjerskih stijena za procjenu rizika od urušavanja (pada) krovine i određivanje oštećenih područja primjenom zabilježenih padova krovine, prije rudarenja metodom širokoga čela. Razmatrana je studija slučaja koja je ispitala model. Rezultati su pokazali da je razina utvrđenoga rizika imala relativno prihvatljivu korelaciju i kompatibilnost s posebnim padom krovine (PPK), s koeficijentom determinacije (R^2) jednakim 0,792 za sve procijenjene indekse ranjivosti (IR) u razmatranim područjima rudarenja. Istražujući i uspoređujući procijenjene vrijednosti indeksa ranjivosti na razmatranim područjima i pripadajućim zabilježenim padovima krovine, otkrivena su oštećena područja unutar onih neoštećenih. Na temelju tih istraživanja izvedene su četiri klase: sigurno, umjereno, opasno i kritično područje, radi identificiranja sigurnih, umjereno opasnih i kritičnih područja prije rudarskih operacija. Rezultati istraživanja pokazali su da je identificiranje štetnih područja razvijenim pristupom prikladno za izradu detaljnoga operativnoga plana za kontrolu pada krovine na širokom čelu. Konačno, model temeljen na inženjerskim sustavima stijena može se koristiti i drugdje za iste uvjete, a predstavljena metodologija može se primijeniti i na ostale dijelove podzemnih rudnika ugljena.

Ključne riječi:
urušavanje krovine, stijenski sustavi, oštećenja područja, rudarenje metodom širokoga čela, rudnik ugljena Parvadeh-I

Authors' contribution

Sajjad Aghababaei (MSc Student, researcher): participated in running models and formulation of simulation and optimization process, initialized the idea. **Gholamreza Saeedi** (Associated Professor): participated in the development of research methodology, verification and evaluation of the models, data analysis and completed literature review. **Hossein Jalalifar** (Full Professor): executed the optimization process, regulated the research process and reviewed the final work.